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TITLE: A SCANNING MICROELLIPSOMETER FOR THE SPATIAL CHARACTERIZATION OF THIN FILMS

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A scanning microellipsometer for the spatial characterization of thin films*

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Abstract

A polarization-modulated ellipsometer was constructed to investigate the optical properties of surfaces and transparent thin films. In the latter case, the measurement gives a unique determination of the index of refraction n and film thickness t. Using a HeNe laser light source, the beam was focused to a spot size of 50 μm. By stepping the sample across the focal point of the laser beam in both x and y directions, the spatial uniformity could be measured.

This apparatus was particularly useful for optical profiling laser-annealed oxide films grown on GaAs. A new technique for laser annealing native oxides on GaAs produced the need for observing spatial structure with spatial resolution of less than 100 μm. Here the laser pulse produced a "crater" in the oxide due to localized healing and subsequent densification of the film (Figs. 1 & 2). This technique allows profiling of film index of refraction and thickness across the laser irradiated area--about 2 to 3 mm in our case. A number of applications in microelectronics are suggested.

Fig. 1. Photo of crater area, the large dots are aluminum contacts for capacitance probing and are 0.5 mm in diameter.

Fig. 2. Scanning electron microscope picture of crater rim running from lower left to upper right. Location from Fig. 1 is lower right quadrant.

Introduction

Ellipsometry is the study of the polarized light reflected from a surface at nonnormal incidence. A Fresnel analysis of the ellipsoid of polarization produces the optical constants of the reflecting surface. For a thin, transparent film on a reflecting substrate, ellipsometric measurements produce parameters related to the film index of refraction and thickness. (Ref. 1, pg. 272)

Commercial instrumentation has been developed for routinely making such measurements. However, such measurements require a fairly large reflecting area. The observation of microstructure with high resolution is not possible.

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Analysis of the contour produced by laser annealing required

(a) a beam dimension of less than 100 μm at the surface under investigation;

(b) translation of the sample in order to profile the crater;

(c) rapid data acquisition for a scanning measurement, and

(d) infrequent calibration.

Equipment

The first two requirements are accomplished with focusing lenses and a calibrated mechanical translation. The regions to be measured are moved stepwise to the focal point of the lens. A measurement is completed in several seconds and a new portion of the sample is stepped into position. This procedure is continued until the desired profile is completed.

To meet the requirements (c) and (d), the polarization-modulation technique of Jasperson et al. is used. The polarization modulator is the key element of the system. Here an isotropic optical element is mechanically coupled to a piezoelectric quartz oscillator. Stress waves are induced in the optical element at the resonant mechanical frequency of the system and stress birefringence produces elliptical polarization of the optical beam at the modulation frequency. (Ref. 1, pg. 415-416, also Refs. 2 & 3)

Here the optical element is fused silica and the driving frequency is 50 kHz. The electrical voltage on the quartz crystal is adjusted to give a maximum phase retardation of approximately 90 deg.

The instrumental configuration shown in Fig. 3 uses the following components:

- Light source was a HeNe laser operating at 632.8-nm wavelength
- Mechanical chopper
- Microscope objective to expand the beam
- Single-element biconvex lens to focus on a 50-μm pinhole
- Pinhole, 50 μm
- Linear polarizer
- Modulator
- Single-element lens with field stop to focus the beam on the sample
- Surface under investigation on the vacuum chuck translator substage
- Single-element lens to focus the reflected beam through the analyzing polarizer
- Analyzing polarizer
- PIN photodiode detector with an interference filter and circular polarizer attached
- Three lock-in amplifiers
- Microcomputer system

The signal from the detector has three frequency components that are measured here. (Ref. 1)

- Mechanical chopper frequency
- Fundamental frequency (50 kHz)
- First harmonic frequency (100 kHz)

Data acquisition

The three components are each synchronously detected and demodulated by lock-in amplifiers whose dc outputs are sampled (in an interlaced manner) by an analog-to-digital converter under the control of the microcomputer. The output of the microcomputer consists of two angular values which are the ellipsometric parameters ψ (psi) and Δ (delta). Using these parameters, the optical constants of the sample can be calculated.

To determine ψ and Δ, a computer program was developed, which requires two calibration readings. Calibration readings were taken every 20 data readings of ψ and Δ. The first calibration is made by inserting a linear polarizer into the beam between the modulator and the sample. Signals at the chopper frequency and first harmonic (100 kHz) are recorded and stored in the computer. The second calibration is made by inserting a quarter-wave plate between the modulator and the linear polarizer. Here the first harmonic and chopper components are recorded and stored. For a sample reading, both the linear polarizer and the quarter-wave plate are removed, and the fundamental, first harmonic, and chopper frequency values are read into the computer.

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SCANNING MICRO-ELLIPSOMETER SYSTEM

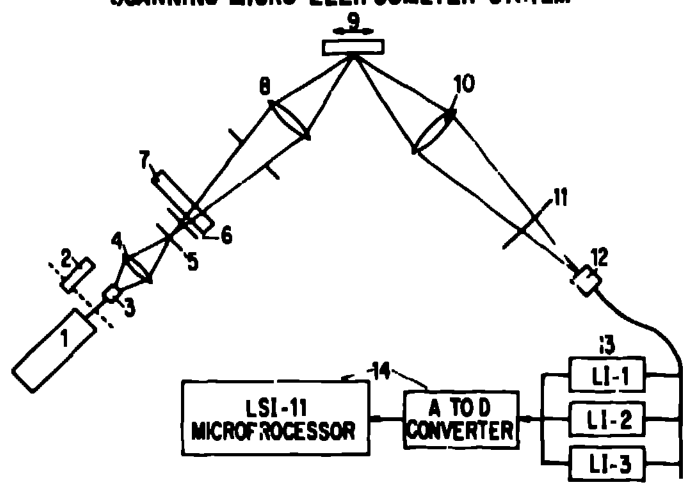

Fig. 3. Schematic diagram of system.

The following equations relate the series of readings to the ellipsometric parameters. (Ref. 1, pg. 260-262) The lock-in voltages for the first harmonic, second harmonic, and chopper frequencies are labeled V_ω, $V_{2\omega}$, V_{ch}, respectively.

$$V_{2\omega}/V_{ch} = B_1 \quad \text{First calibration readings}$$

$$V_\omega/V_{ch} = B_2 \quad \text{Second calibration readings}$$

$$\left.\begin{array}{l} V_{2\omega}/V_{ch} = A_1 \\ V_\omega/V_{ch} = A_2 \end{array}\right) \quad \text{Sample readings}$$

$$A_1/B_1 = \cos 2\psi \therefore \psi = \frac{\cos^{-1}(A1/B1)}{2}$$

and

$$A_2/B_2 = C \therefore \Delta = \sin^{-1}\left(\frac{C}{\sin 2\psi}\right)$$

At the time of initial calibration and alignment, the phasing of each amplifier is standardized in such a manner that for all subsequent samples the output polarity is used to determine the proper angular ranges for ψ and Δ. The sign of $V_{2\omega}$ is used to determine if ψ is less than or greater than 45 deg.

The sign of the V_ω signal indicates whether Δ is to be found between 0 and 180 deg or between 180 and 360 deg. This gives one value for ψ and two possible values for Δ, only one of which is correct.

Data analysis

Figure 4 is assumed to be the correct model of the system under investigation. Where N is the index of refraction of the material, ϕ is the angle of incidence or refraction, and λ is the wavelength of the incident light. In general, $N_0 = 1$, N_1 is real, N_2 is complex, and D is film thickness.

The basic parameters for this system are:

The Fresnel reflection coefficients for parallel and perpendicular components,

$$p_{01} = \frac{N_1 \cos\phi_0 - N_0 \cos\phi_1}{N_1 \cos\phi_0 + N_0 \cos\phi_1} \qquad s_{01} = \frac{N_0 \cos\phi_0 - N_1 \cos\phi_1}{N_0 \cos\phi_0 + N_1 \cos\phi_1}$$

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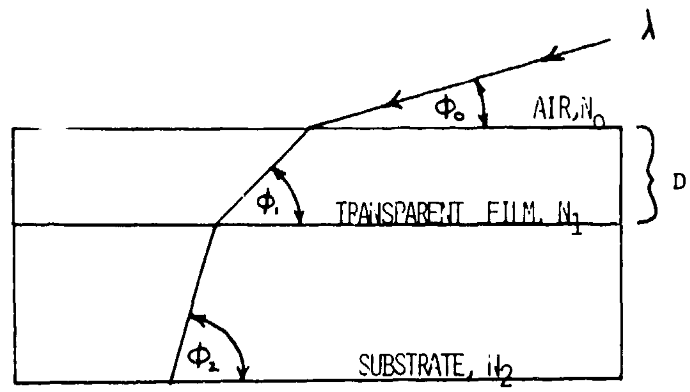

Fig. 4. Ideal model of system to be measured.

$$p_{12} = \frac{N_2 \cos\phi_1 - N_1 \cos\phi_2}{N_2 \cos\phi_1 + N_1 \cos\phi_2} \qquad s_{12} = \frac{N_1 \cos\phi_1 - N_2 \cos\phi_2}{N_1 \cos\phi_1 + N_2 \cos\phi_2}$$

With Drude's formula giving the relationship between the ellipsometric parameters, ψ and Δ, and the basic parameters:

$$\tan\psi e^{i\Delta} = \frac{(p_{01} + p_{12}x)(1 + s_{01}\, s_{12}x)}{(1 + p_{01}\, p_{12}x)\,(s_{01} + s_{12}x)}$$

where

$$x = \exp\left\{-i\left[4\pi(D/\lambda)(N_1^2 - N_0^2 \sin^2 \phi_0)^{1/2}\right]\right\}$$

A program was written using an iterative technique to determine the following values:

N_1, D

when these values were known:

N_0, ϕ_0, N_2, λ, ψ, Δ

As stated above, the measurement produces two values of Δ but only one corresponds to the physical situation. Also, as more than one value of thickness can have the same ψ and Δ associated with it, the operator must have an estimate of the thickness or index of refraction. When both values of Δ give answers that are possible, a change in the angle of incidence will resolve the ambiguity.

Variations in the angle of incidence caused two types of errors in determining ψ and Δ in this experiment. The first source of error was due to the slope in the laser-annealed spot. This error was negligible except near the "crater" edges. The anomalies occurring there are evident in the data. The second source of error arises from the use of a convergent light beam. Here, in effect, there is a range of incident angles. The net ψ and Δ determined are thus only an approximation to the real ψ and Δ, which would be determined using a collimated light source at the "average" angle of incidence, 70 deg. Svitashev et al., (Ref. 4) have analyzed in detail the errors arising because of this. We have used the results of computer simulations and also comparisons of measurements made with both collimated and convergent light beams on spatially uniform samples. In this way, for the system under investigation we have estimated our error to be +1% in both thickness and refractive index for these films.

Results

Using this technique, the optical constants and physical thickness of an area can be profiled in detail, as shown in Fig. 5. Other measurement methods have been used and support the data produced by this method, as shown in Fig. 6. In particular, ion backscattering confirms the relative changes in oxide thickness.

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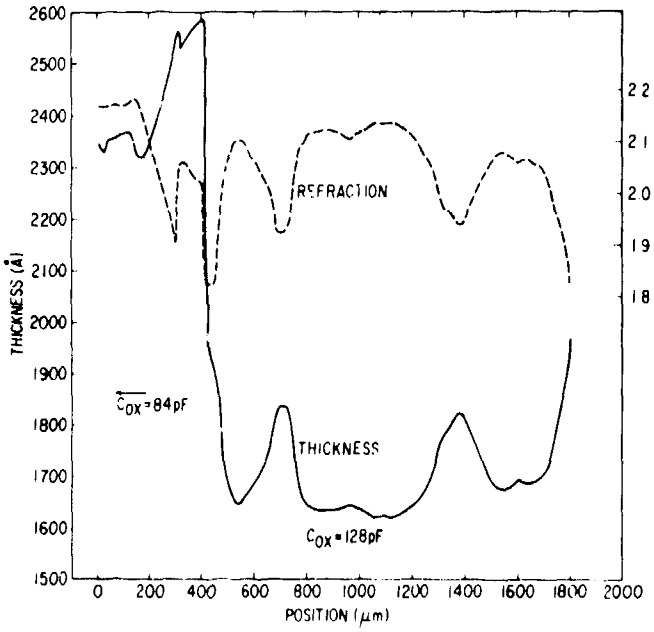

Fig. 5. Optical profile of one wall and through center of crater.

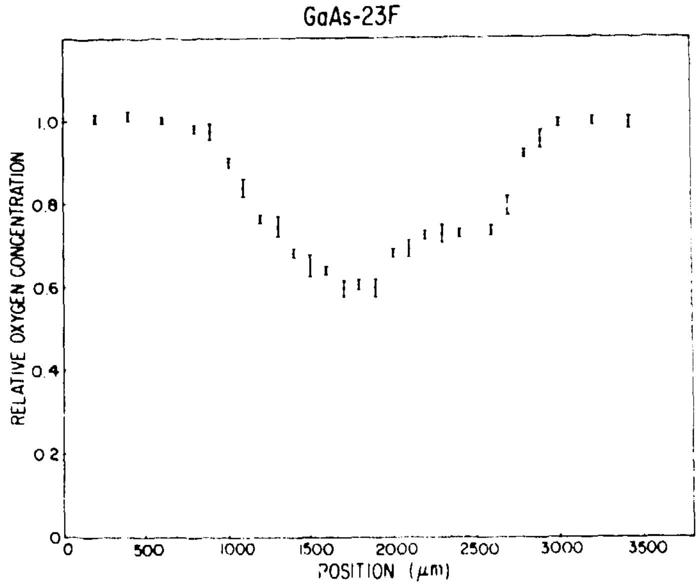

Fig. 6. Profile as obtained from the Laboratory nuclear microprobe.

Applications

This technique is useful for the spatial characterization of thickness, optical constants, and homogeneity of a sample. Although the system is somewhat expensive and difficult to construct and align, accurate results are produced.

Further refinement in the apparatus that may be valuable are:

- Computer-controlled insertion and removal of the calibration polarizers
- Computer-controlled stepping of sample
- Achromatizing the optical elements and the use of a monochrometer for spectral as well as spatial characterization of the sample.

Acknowledgment

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